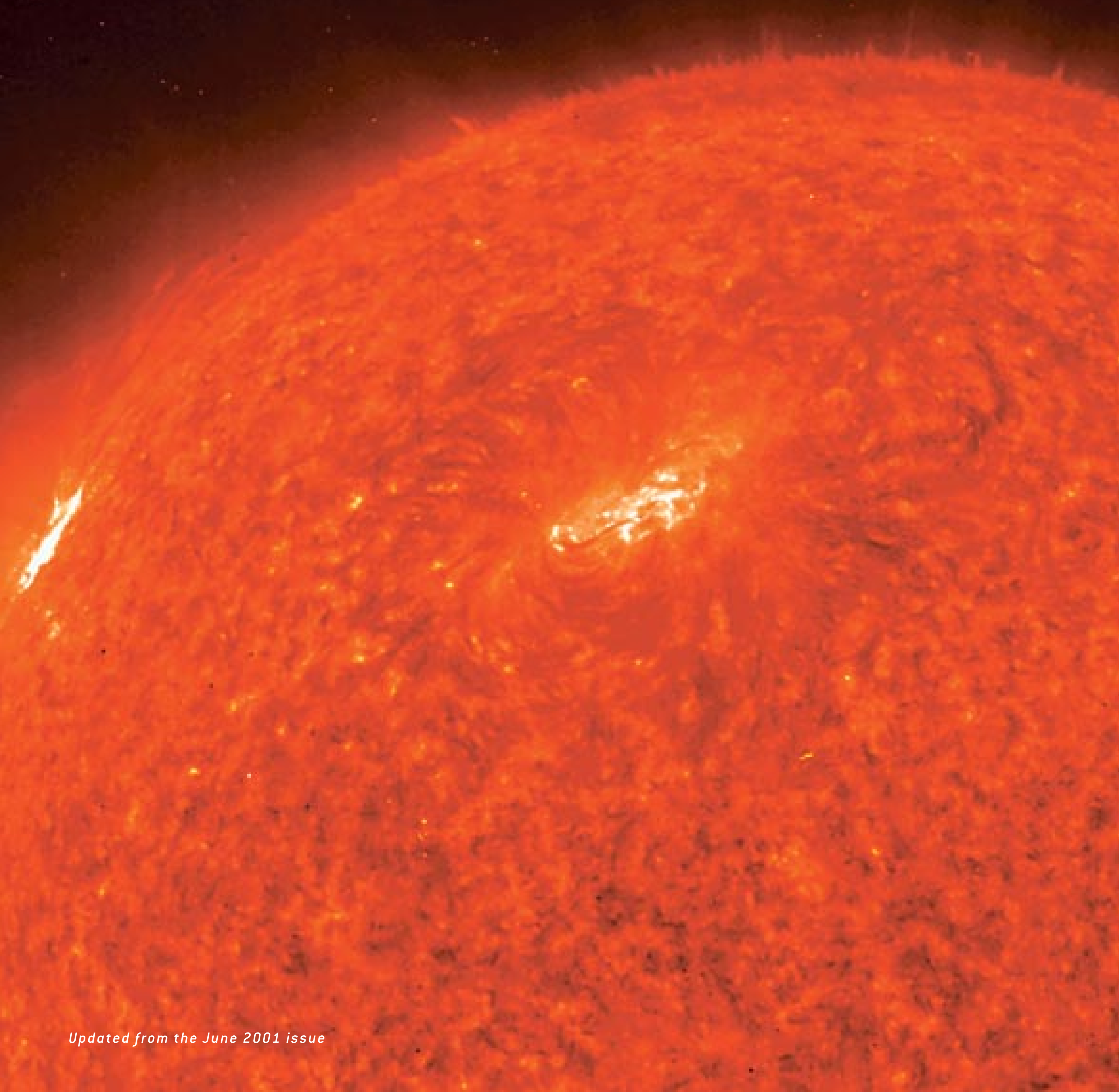
Like a boiling teakettle atop a **COLD** stove,

the sun's **HOT** outer layers sit on the relatively cool surface.

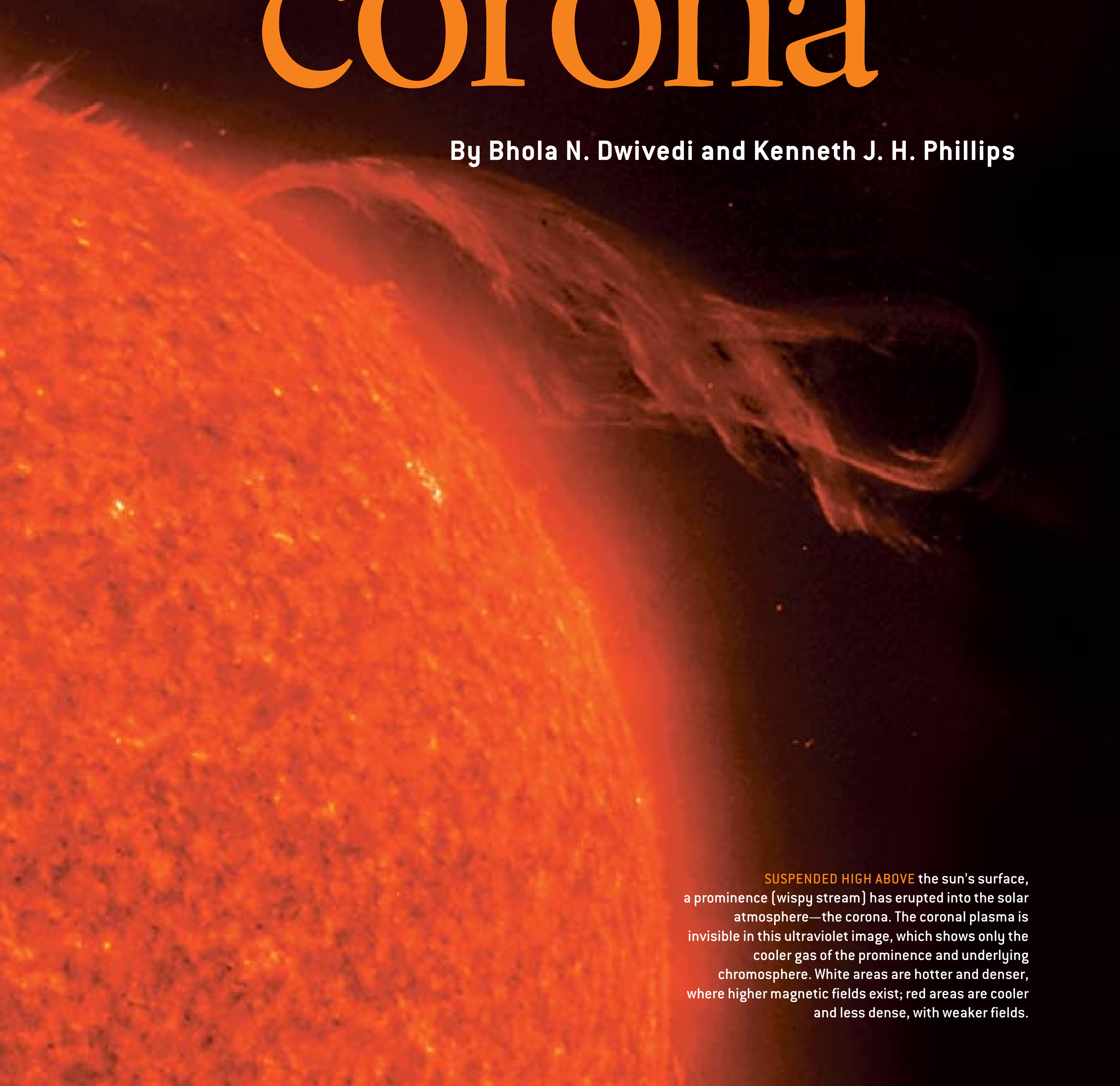
And now astronomers are **FIGURING OUT WHY**



*Updated from the June 2001 issue*

# the paradox of the sun's hot corona

By Bhola N. Dwivedi and Kenneth J. H. Phillips



SUSPENDED HIGH ABOVE the sun's surface, a prominence (wispy stream) has erupted into the solar atmosphere—the corona. The coronal plasma is invisible in this ultraviolet image, which shows only the cooler gas of the prominence and underlying chromosphere. White areas are hotter and denser, where higher magnetic fields exist; red areas are cooler and less dense, with weaker fields.

**Relatively few people have witnessed a total** eclipse of the sun—one of nature's most awesome spectacles. It was therefore a surprise for inhabitants of central Africa to see two total eclipses in quick succession, in June 2001 and December 2002. Thanks to favorable weather along the narrow track of totality across the earth, the 2001 event in particular captivated residents and visitors in Zambia's densely populated capital, Lusaka. One of us (Phillips), with colleagues from the U.K. and Poland, was also blessed with scientific equipment that worked perfectly on location at the University of Zambia. Other scientific teams captured valuable data from Angola and Zimbabwe. Most of us were trying to find yet more clues to one of the most enduring conundrums of the solar system: What is the mechanism that makes the sun's outer atmosphere, or corona, so hot?

The sun might appear to be a uniform sphere of gas, the essence of simplicity. In actuality it has well-defined layers that can loosely be compared to a planet's solid part and atmosphere. The solar radiation that we receive ultimately derives from nuclear reactions deep in the core. The energy gradually leaks out until it reaches the visible surface, known as the photosphere, and escapes into space. Above that surface is a tenuous atmosphere. The lowest part, the chromosphere, is usually visible only during total eclipses, as a bright red crescent. Beyond it is the pearly white corona, extending millions of kilometers. Further still, the corona becomes a stream of charged particles—the solar wind that blows through our solar system.

Journeying out from the sun's core, an imaginary observer first encounters temperatures of 15 million kelvins, high enough to generate the nuclear reactions that power the sun. Temperatures get progressively cooler en route to the photosphere, a mere 6,000 kelvins. But then an unexpected thing happens: the temperature gradient reverses. The chromosphere's temperature steadily rises to 10,000 kelvins, and going into the corona, the temperature jumps to one million kelvins. Parts of the corona associated with sunspots get even hotter. Considering that the energy must originate below the photosphere, how can this be? It is as if you got warmer the farther away you walked from a fireplace.

The first hints of this mystery emerged in the 19th century when eclipse observers detected spectral emission lines that no known element could account for. In the 1940s physicists associated two of these lines with iron atoms that had lost up to half their normal retinue

NASA GODDARD SPACE FLIGHT CENTER (*preceding page*); TRACE/NASA (*below*)

CORONAL LOOP, seen in ultraviolet light by the TRACE spacecraft, extends 120,000 kilometers off the sun's surface.

X-RAY IMAGE from the Yohkoh spacecraft shows structures both bright (associated with sunspots) and dark (polar coronal holes).

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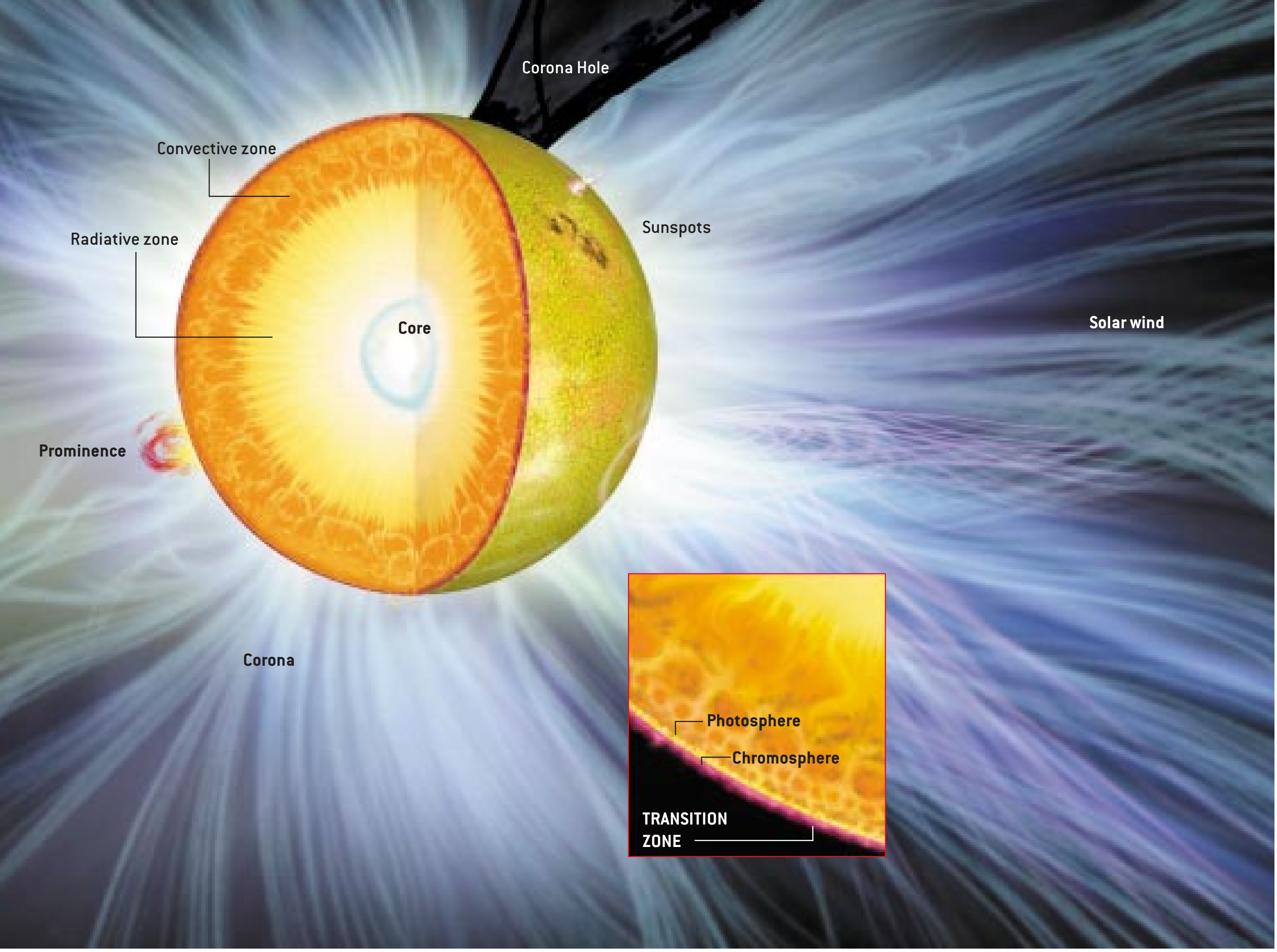
of 26 electrons—a situation that requires extremely high temperatures. Later, instruments on rockets and satellites found that the sun emits copious x-rays and extreme ultraviolet radiation—as can be the case only if the coronal temperature is measured in megakelvins. Nor is this mystery confined to the sun: most sunlike stars appear to have x-ray-emitting atmospheres.

At last, however, a solution seems to be within our grasp. Astronomers have long implicated magnetic fields in the coronal heating; where those fields are strongest, the corona is hottest. Such fields can transport energy in a form other than heat, thereby sidestepping the usual thermodynamic restrictions. The energy must still be converted to heat, and researchers are testing two possible theories: small-scale magnetic field reconnections—the same process involved in solar flares—and magnetic waves. Important clues have come from complementary observations: spacecraft can observe at wavelengths inaccessible from the ground, while ground-based telescopes can gather reams of data unrestricted by the bandwidth of orbit-to-Earth radio links. The findings may be crucial to understanding how events on the sun affect the atmosphere of Earth [see "The Fury of Space Storms," by James L. Burch; SCIENTIFIC AMERICAN, April 2001].

The first high-resolution images of the corona came from the ultraviolet and x-ray telescopes on board Skylab, the American space station inhabited in 1973 and




DON DIXON

FAR FROM A UNIFORM BALL of gas, the sun has a dynamic interior and atmosphere that heat and light our solar system.

1974. Pictures of active regions of the corona, located above sunspot groups, revealed complexes of loops that came and went in a matter of days. Much larger but more diffuse x-ray arches stretched over millions of kilometers, sometimes connecting sunspot groups. Away from active regions, in the "quiet" parts of the sun, ultraviolet emission had a honeycomb pattern related to the large convection granules in the photosphere. Near the solar poles and sometimes in equatorial locations were areas of very faint x-ray emission—the so-called coronal holes.

## Connection to the Starry Dynamo

EACH MAJOR SOLAR SPACECRAFT since Skylab has offered a distinct improvement in resolution. From 1991 to late 2001, the x-ray telescope on the Japanese Yohkoh spacecraft routinely imaged the sun's corona, tracking the evolution of loops and other features through one complete 11-year cycle of solar activity. The Solar and Heliospheric Observatory (SOHO), a joint European-American satellite launched in 1995, orbits a point 1.5 million kilometers from Earth on its sunward side, giving the spacecraft the advantage of an uninterrupted view of the sun [see "SOHO Reveals the Secrets of the Sun," by Kenneth R. Lang; Scientific American, March 1997]. One of its instruments, called the Large Angle and Spectroscopic Coronagraph (LASCO), observes in visible light using an opaque disk to mask out the main part of the sun. It has tracked large-scale coronal structures as they rotate with the rest of the sun (a period of about 27 days as seen from Earth). The images show huge bubbles of plasma known as coronal mass ejections, which move at up to 2,000 kilometers a second, erupting from the corona and occasionally colliding with Earth and other planets. Other SOHO instruments, such as the Extreme Ultraviolet Imaging Telescope, have greatly improved on Skylab's pictures.

The Transition Region and Coronal Explorer (TRACE) satellite, operated by the Stanford-Lockheed Institute for Space Research, went into a polar orbit around Earth in 1998. With unprecedented resolution, its ultraviolet telescope has revealed a vast wealth of detail. The active-region loops are now known to be threadlike features no more than a few hundred kilometers wide. Their incessant flickering and jouncing hint at the origin of the corona's heating mechanism.

The latest spacecraft dedicated to the sun is the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), launched in 2002, which is providing images and spectra in the x-ray region of wavelengths less than four nanometers. Because solar activity has been high, much of its early attention was focused on intense flares, but as the solar minimum approaches, investigators will increasingly be interested in tiny microflares, a clue to the corona's heating mechanism.

The loops, arches and coronal holes trace out the sun's magnetic fields. The fields are thought to originate in the upper third of the solar interior, where energy is transported mostly by convection rather than radiation. A combination of convection currents and differential rotation—whereby low latitudes rotate slightly faster than higher latitudes—twist the fields to form ropelike or other tightly bound configurations that eventually emerge at the photosphere and into the solar atmosphere. Particularly intense fields are marked by sunspot groups and active regions.

For a century, astronomers have measured the magnetism of the photosphere using magnetographs, which observe the Zeeman effect: in the presence of a magnetic field, a spectral line can split into two or more lines with slightly different wavelengths and polarizations. But Zeeman observations for the corona have yet to be done. For the spectral lines that the corona emits, the splitting is too small to be detected with present instruments, so astronomers have had to resort to mathematical extrapolations from the photospheric field. These extrapolations predict that the magnetic field of the corona generally has a strength of about 10 gauss, 20 times Earth's magnetic field strength at its poles. In active regions, the field may reach 100 gauss.

## Space Heaters

THESE FIELDS ARE WEAK compared with those that can be produced with laboratory magnets, but they have a decisive influence in the solar corona. This is because the corona's temperature is so high that it is almost fully ionized: it is a plasma, made up not of neutral atoms but of electrons, protons and other atomic nuclei. Plasmas undergo a wide range of phenomena that neutral gases do not. The magnetic fields of the corona are strong enough to bind the charged particles to the field lines. Particles move in tight helical paths up and down these field lines like very small beads on very long strings. The limits on their motion explain the sharp boundaries of features such as coronal holes. Within the tenuous plasma, the magnetic pressure (proportional to the strength squared) exceeds the thermal pressure by a factor of at least 100.

One of the main reasons astronomers are confident that magnetic fields energize the corona is the clear relation between field strength and temperature. The bright loops of active regions, where there are extremely strong fields, have a temperature of about four million kelvins. But the giant arches of the quiet-sun corona, characterized by weak fields, have a temperature of about one million kelvins.

Until recently, however, ascribing coronal heating to magnetic fields ran into a serious problem. To convert field energy to heat energy, the fields must be able to diffuse through the plasma, which requires that the corona have a certain amount of electrical resistivity—in other words, that it not be a perfect conductor. A perfect conductor cannot sustain an electric field, because charged particles instantaneously reposition themselves to neutralize it. And if a plasma cannot sustain an electric field, it cannot move relative to the magnetic field (or vice versa), because to do so would induce an electric field. This is why astronomers talk about magnetic fields being "frozen" into plasmas.

This principle can be quantified by considering the time it takes a magnetic field to diffuse a certain distance through a plasma. The diffusion rate is inversely proportional to resistivity. Classical plasma physics assumes that electrical resistance arises from so-called Coulomb collisions: electrostatic forces from charged particles deflect the flow of electrons. If so, it should take about 10 million years to traverse a distance of 10,000 kilometers, a typical length of active-region loops.

Events in the corona—for example, flares, which may last for only a few minutes—far outpace that rate. Either the resistivity is unusually high or the diffusion distance is extremely small, or both. A distance as short as a few meters could occur in certain structures, accompanied by a steep magnetic gradient. But researchers have come to realize that the resistivity could be higher than they traditionally thought.

## Raising the Mercury

ASTRONOMERS HAVE TWO basic ideas for coro-

THE AUTHORS

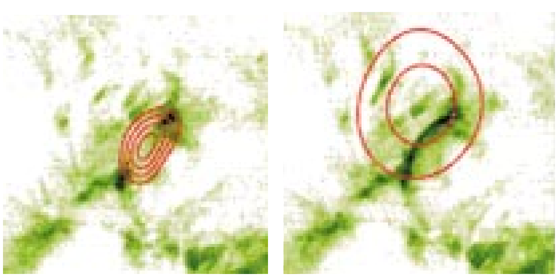
*BHOLA N. DWIVEDI* and *KENNETH J. H. PHILLIPS* began collaborating on solar physics a decade ago. Dwivedi teaches physics at Banaras Hindu University in Varanasi, India. He has been working with SUMER, an ultraviolet telescope on the SOHO spacecraft, for more than 10 years; the Max Planck Institute for Aeronomy near Hannover, Germany, recently awarded him one of its highest honors, the Gold Pin. As a boy, Dwivedi studied by the light of a homemade burner and became the first person in his village ever to attend college. Phillips recently left the Rutherford Appleton Laboratory in England to become a senior research associate in the Reuven Ramaty High Energy Solar Spectroscopic Imager group at the NASA Goddard Space Flight Center in Greenbelt, Md. He has worked with x-ray and ultraviolet instruments on numerous spacecraft—including OSO-4, SolarMax, IUE, Yohkoh, Chandra and SOHO—and has observed three solar eclipses using CCD cameras.

nal heating. For years, they concentrated on heating by waves. Sound waves were a prime suspect, but in the late 1970s researchers established that sound waves emerging from the photosphere would dissipate in the chromosphere, leaving no energy for the corona itself. Suspicion turned to magnetic waves. Such waves might be purely magnetohydrodynamic (MHD)—so-called Alfvén waves—in which the field lines oscillate but the pressure does not. More likely, however, they share characteristics of both sound and Alfvén waves.

MHD theory combines two theories that are challenging in their own right—ordinary hydrodynamics and electromagnetism—although the broad outlines are clear. Plasma physicists recognize two kinds of MHD pressure waves, fast and slow mode, depending on the phase velocity relative to an Alfvén wave—around 2,000 kilometers a second in the corona. To traverse a typical active-region loop requires about five seconds for an Alfvén wave, less for a fast MHD wave, but at least half a minute for a slow wave. MHD waves are set into motion by convective perturbations in the photosphere and transported out into the corona via magnetic fields. They can then deposit their energy into the plasma if it has sufficient resistivity or viscosity.

A breakthrough occurred in 1998 when the TRACE spacecraft observed a powerful flare that triggered waves in nearby fine loops. The loops oscillated back and forth several times before settling down. The damping rate was millions of times as fast as than classical theory predicts. This landmark observation of "coronal seismology" by Valery M. Nakariakov, then at the University of St. Andrews in Scotland, and his colleagues has shown that MHD waves could indeed deposit their energy into the corona.

An intriguing observation made with the ultraviolet coronagraph on the SOHO spacecraft has shown that highly ionized oxygen atoms have temperatures in coronal holes of more than 100 million kelvins, much higher than those of electrons and protons in the plasma. The temperatures also seem higher perpendicular to the magnetic field lines than parallel to them. Whether this is important for corona heating remains to be seen.



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Despite the plausibility of energy transport by waves, a second idea has been ascendant: that coronal heating is caused by very small, flarelike events. A flare is a sudden release of up to $10^{25}$ joules of energy in an active region of the sun. It is thought to be caused by reconnection of magnetic field lines, whereby oppositely directed lines cancel each other out, converting magnetic energy into heat. The process requires that the field lines be able to diffuse through the plasma.

A flare sends out a blast of x-rays and ultraviolet radiation. At the peak of the solar cycle (reached in 2000), several flares an hour may burst out across the sun. Spacecraft such as Yohkoh and SOHO have shown that much smaller but more frequent events take place not only in active regions but also in regions otherwise deemed quiet. These tiny events have about a millionth the energy of a full-blown flare and so are called microflares. They were first detected in 1980 by Robert P. Lin of the University of California at Berkeley and his colleagues with a balloon-borne hard x-ray detector. During the solar minimum in 1996, Yohkoh also recognized events with energy as small as 0.01 of a microflare.

Early results from RHESSI indicate more than 10 hard x-ray microflares an hour. In addition, RHESSI can produce images of microflares, which was not possible before. As solar activity declines, RHESSI should be able to locate and characterize very small flares.

Flares are not the only type of transient phenomena. X-ray and ultraviolet jets, representing columns of coronal material, are often seen spurting up from the lower corona at a few hundred kilometers a second. But tiny x-ray flares are of special interest because they reach the megakelvin temperatures required to heat the corona. Several researchers have attempted to extrapolate the microflare rates to even tinier nanoflares, to test an idea raised some years ago by Eugene Parker of the University of Chicago that numerous nanoflares occurring outside of active regions could account for the entire energy of the corona. Results remain confusing, but perhaps the combination of RHESSI, TRACE and SOHO data during the forthcoming minimum can provide an answer.

Which mechanism—waves or nanoflares—dominates? It depends on the photospheric motions that perturb the magnetic field. If these motions operate on timescales of half a minute or longer, they cannot trigger MHD waves. Instead they create narrow current sheets in which reconnections can occur. Very high resolution optical observations of bright filigree structures by the Swedish Vacuum Tower Telescope on La Palma in the Canary Islands—as well as SOHO and TRACE observations of a general, ever changing "magnetic carpet" on the surface of the sun—demon-

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strate that motions occur on a variety of timescales. Although the evidence now favors nanoflares for the bulk of coronal heating, waves may also play a role.

## Fieldwork

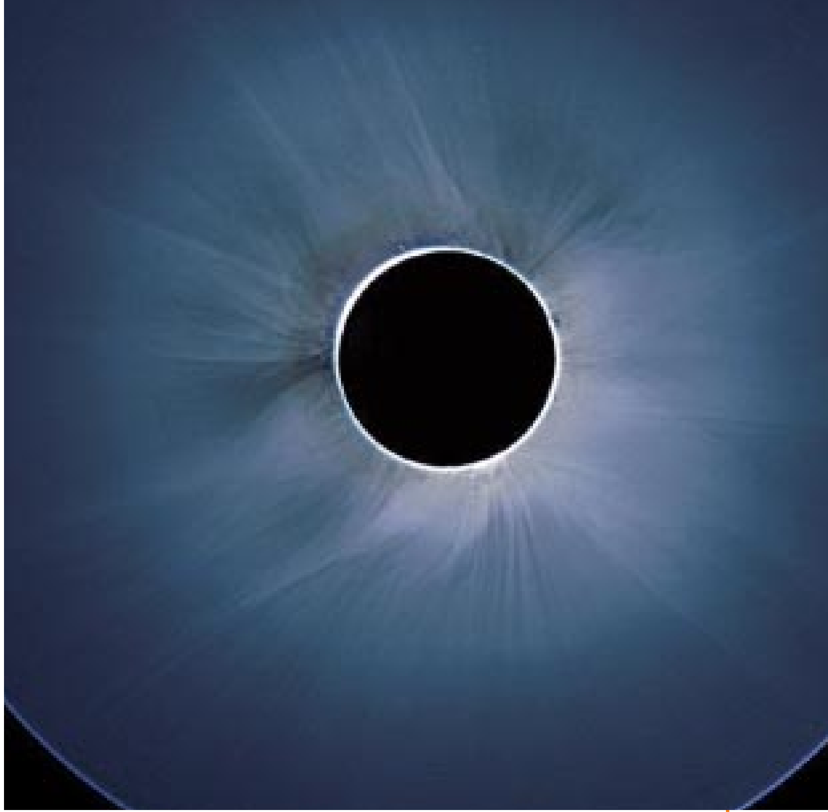
IT IS UNLIKELY, for example, that nanoflares have much effect in coronal holes. In these regions, the field lines open out into space rather than loop back to the sun, so a reconnection would accelerate plasma out into interplanetary space rather than heat it. Yet the corona in holes is still hot. Astronomers have scanned for signatures of wave motions, which may include periodic fluctuations in brightness or Doppler shift. The difficulty is that the MHD waves involved in heating probably have very short periods, perhaps just a few seconds. At present, spacecraft imaging is too sluggish to capture them.

For this reason, ground-based instruments remain important. A pioneer in this work has been Jay M. Pasachoff of Williams College. He and his students have used high-speed detectors and CCD cameras to look for modulations in the coronal light during eclipses. Analyses of his best results indicate oscillations with periods of one to two seconds. Serge Koutchmy of the Institute of Astrophysics in Paris, using a coronagraph, has found evidence of periods equal to 43, 80 and 300 seconds.

The search for those oscillations is what led Phillips and his colleagues to Bulgaria in 1999 and Zambia in 2001. Our instrument consists of a pair of fast-frame CCD cameras that observe both white light and the green spectral line produced by highly ionized iron. A tracking mirror, or heliostat, directs sunlight into a horizontal beam that passes into the instrument. At our observing sites, the 1999 eclipse totality lasted two minutes and 23 seconds, the 2001 totality three minutes and 38 seconds. Analyses of the 1999 eclipse by David A. Williams, now at University College London, reveal the possible presence of an MHD wave with fast-mode characteristics moving down a looplike structure. The CCD signal for this eclipse is admittedly weak, however, and Fourier analysis by Pawel Rudawy at Wroclaw the University of in Poland fails to find significant periodicities in the 1999 and 2001 data. We continue to try to determine if there are other, nonperiodic changes.

Insight into coronal heating has also come from observations of other stars. Current instruments cannot see surface features of these stars directly, but spectroscopy can deduce the presence of starspots, and ultraviolet and x-ray observations can reveal coronae and flares, which are often much more powerful than their solar counterparts. High-resolution spectra from the Extreme Ultraviolet Explorer and the latest x-ray satellites, Chandra and XMM-Newton, can probe temperature and density. For example, Capella—a stellar system consisting of two giant stars—has photospheric temperatures like the sun's but coronal temperatures that are six times higher. The intensities of individual spectral lines indicate a plasma density of about 100 times that of the solar corona. This high density implies that Capella's coronae are much smaller than the sun's, stretching out a tenth or less of a stellar diameter. Apparently, the distribution of the magnetic field differs from star to star. For some stars, tightly orbiting planets might even play a role.

Even as one corona mystery begins to yield to our concerted efforts, additional ones appear. The sun and other stars, with their complex layering, magnetic fields and effervescent dynamism, still manage to defy our understanding. In an age of such exotica as black holes and dark matter, even something that seems mundane can retain its allure. SA



ORDINARY LIGHT, EXTRAORDINARY SIGHT: the corona photographed in visible light on August 11, 1999, from Chadegan in central Iran.



### MORE TO EXPLORE

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